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SPECTRAL AMPLITUDE AND PHASE EVOLUTION IN PETAWATT LASER PULSES

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Spectral amplitude and phase evolution in petawatt laser pulses

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Abstract: The influence of the active gain medium on the spectral amplitude and phase of amplified pulses in a CPA system is studied. Results from a 10-PW example based on Nd-doped mixed glasses are presented.

OCIS codes: (140.7090) Ultrafast lasers; (320.5540) Pulse shaping

Petawatt (PW) laser pulses are produced today using the chirped-pulse amplification (CPA) technique. Two CPA systems have shown significant potential. The first is based on Ti:Sapphire crystals and can generate PW pulses with durations below 30fs. The second is based on Nd-doped glass and can produce 440 fs pulses with 660 J of energy [1]. Using a combination of two different glasses in the amplifier, more bandwidth can be generated in glass systems and PW pulses as short as 167 fs have been produced [2].

The spectrum of the amplified pulses in Nd:glass systems is shaped by two effects, gain narrowing and gain saturation. For Nd:Glass systems, gain saturation is reached near 5 J/cm^2, close to the damage threshold of the glass and the optics involved in the beam transportation. In addition, non-linear effects become important due to the high intensity of the laser pulse. In spite of these difficulties, using spectral filters to "push down" on the amplification at the peak gain wavelengths, it is possible to trigger an early onset of the gain saturation effect with significant benefits. More bandwidth can be amplified, increasing the duration of the stretched pulse and thus lowering the B-integral. Less energy is extracted but within shorter pulses. This study addresses specific issues of a laser that balances the mixed-glass, spectral filtering, and gain saturation concepts to generate 10PW pulses.

A one-dimensional code that accounts for the energy and gain in the glass for each frequency in the stretched pulse is used to model the amplification. Linear losses are neglected. For the purpose of the modeling the properties of the glasses were taken to be similar to those of: Nd:Phosphate (APG-1, 27.8 nm linewidth) and Nd:Silicate (K-824, 38.2 nm linewidth). The stimulated emission cross sections were approximated as Lorentzian functions with the above-mentioned linewidths. These curves are shown in Fig. 1a. The amplification of the phosphate and the silicate glasses peaks at 1053.9 nm and 1064.5 nm, respectively.

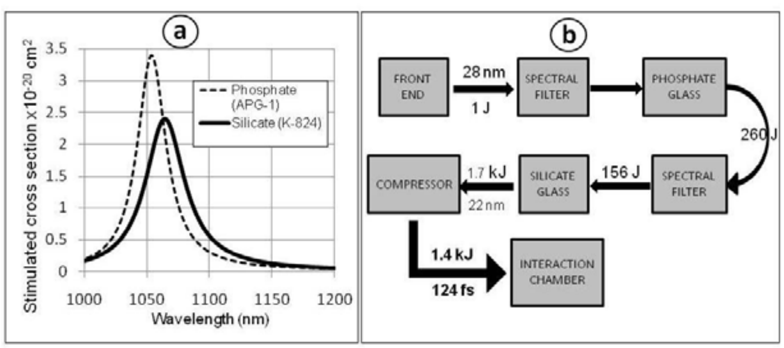

Fig. 1 Lorentzian functions that approximate the stimulated emission cross-sections for the phosphate and silicate glasses, a, and, the 10-PW mixed-glass laser system schematic, b.

The schematic of the 10-PW system is shown in Fig. 1b. The main components of the laser are the front end and the two glass-based modules each containing two double-passed sets of disk amplifiers. The front end could be based on a Ti:sapphire system and an OPCPA amplifier with multiple stages, similar to the one demonstrated in Ref. [2]. In this computer model, the front end generates a chirped pulse derived from a 60-fs Gaussian pulse centered at 1066 nm. The energy in the pulse is 1 J and the FWHM bandwidth is 28 nm. The spectrum of this input pulse is shown in Fig. 2a, line i (input). Next, the pulse passes through a spectral filter that is designed to introduce losses near the 1053.9-nm peak amplification wavelength of the phosphate glass. The transmitted spectrum is shown in Fig. 2a, line f (filter). Then, the phosphate-based series of amplifiers with a 9.4 cm aperture boosts the energy to 260 J while pulling the spectrum towards 1053 nm and shrinking the bandwidth to 15 nm. The resultant spectrum is shown in Fig. 2a, line p (phosphate). Some saturation occurs in the last disks of the amplifier as the fluence reaches 3.7 J/cm^2. The next spectral filter, see Fig. 1b, pushes down on the spectrum near 1064.5 nm and reduces the energy to 156 J. The transmitted spectrum is not shown in Fig. 2a for visibility reasons. The following 20.8 cm amplifier module brings the energy up to 1.7 kJ but the pulse still maintains a significant bandwidth of 22 nm, mainly due to the strong seeding on the blue side and gain saturation on the red side. The spectrum is shown in Fig. 2a, line s (silicate). If a stretching factor of 200ps/nm is considered, the chirped pulse duration would be 4.4 ns, long enough for the non linear effects not to be significant. The pulse is then compressed in a vacuum compressor with an estimated 80% transmission. The energy available for experiments in the interaction chamber is 1.4 kJ provided that large optics with high damage thresholds are used.

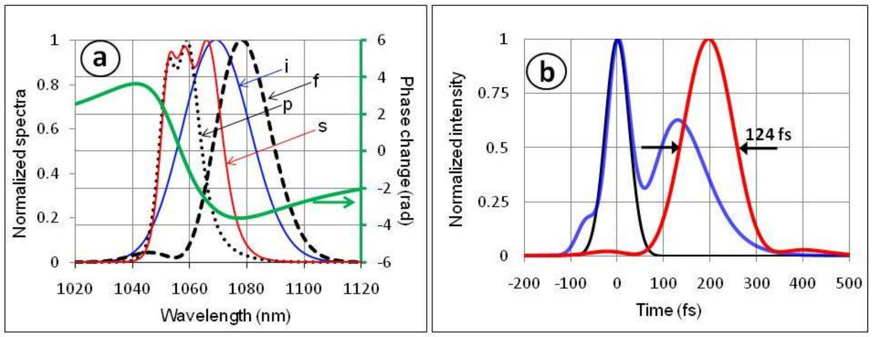

Fig. 2. Normalized spectra of the pulse at various points during amplification (left axis, i-input 60-fs pulse, f-after 1st spectral filter, p-after phosphate, and s-after silicate amplifier) and added phase (green curve, right axis) due to the resonant active medium, a; pulse shapes (black-input 60-fs Gaussian pulse, blue- FFT reconstruction with the spectrum of the initial 60-fs pulse and the added phase during amplification, red-FFT reconstruction with the final amplified spectrum and the added resonant phase compensated with a phase shaper, b.

The recompression of the pulse depends on the stretcher-amplifier-compressor design, non linear phase distortions and resonant phase distortions. The resonant phase change is due to the active medium and is a function of the power gain in each glass module and the glass linewidth:

$$\Delta\emptyset_{res}(\omega) = \frac{\omega-\omega_p}{\Delta\omega_p}\ln G_p(\omega)+\frac{\omega-\omega_s}{\Delta\omega_s}\ln G_s(\omega), \qquad (1)$$

where ω_p, $\Delta\omega_p$ and ω_s, $\Delta\omega_s$ are the peak angular frequencies and linewidths of the phosphate and the silicate glasses, respectively. The power gain coefficients G_p and G_s, respectively, are functions of the frequency as a result of the gain saturation. The total resonant phase added to the pulse is shown in Fig 2a on the left axis. The influence of this phase on the pulse shape is shown in Fig. 2b. The black curve is the initial 60-fs pulse. The blue curve is a pulse reconstructed through a Fourier transform from the initial spectrum shown in Fig. 2a, line i (input), with the phase shown in Fig. 2a. This curve shows the importance of the resonant phase distortions for laser systems where: a, large gains are needed, and, b, wide bandwidths are amplified. A large part of this phase can be compensated for with phase shaping devices. The red curve in Fig. 2b shows a 124 fs pulse which is the shortest pulse obtainable from the 22-nm final spectrum (Fig. 2a, line s) and the phase that can be compensated with mainly a 3rd order dispersion factor of 7×10^5 fs^3. Knowing ahead the compensation factors is important for single-shot systems.

In conclusion, this study shows that, by using spectral shaping and gain saturation in a mixed-glass amplifier, it is possible to produce 124 fs, 1.4 kJ laser pulses. One detrimental effect, the pulse distortion due to resonant amplification medium, has been investigated and its magnitude as well as its compensation calculated.

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